

# Top Quark Studies at D0

**Reinhild Yvonne Peters**

University of Manchester, School of Physics and Astronomy, Oxford Road, Manchester M13 9PL, England; also at DESY, Hamburg, Germany

E-mail: [reinhild.peters@cern.ch](mailto:reinhild.peters@cern.ch)

**Abstract.** Years after its discovery in 1995 by CDF and D0, the top quark still undergoes intense investigations at the Tevatron. Using up to the full Run II data sample, new measurements of top quark production and properties by the D0 Collaboration are presented. In particular, the first observation of single top quark s-channel production, the measurement of differential  $t\bar{t}$  distributions, forward-backward  $t\bar{t}$  asymmetry, a new measurement of the top quark mass, and a measurement of the top quark charge are discussed.

## 1. Introduction

The top quark, discovered in 1995 by the CDF and D0 Collaborations at the Fermilab Tevatron collider, is the heaviest known elementary particle [1, 2]. Due to its high mass and short lifetime, the top quark provides a unique environment to study a bare quark. It is believed to play a special role in electroweak symmetry breaking and provide a window to physics beyond the standard model (SM).

Despite the currently running LHC  $pp$  collider being a top quark factory, the study of the top quark using Run II Tevatron  $p\bar{p}$  collision events provides complementary information. Tevatron Run II with a collision energy of 1.96 TeV (starting 2001 and ending September 30th, 2011) provided  $\approx 10.5 \text{ fb}^{-1}$  of integrated luminosity for each of the D0 and CDF experiments.

In this article, latest studies in single top quark production and top quark pair production at the D0 experiment are presented. The discussed analyses are performed in dileptonic and semileptonic final states, where either both or one of the  $W$  bosons, coming from the decay of the top quark, decay into a charged lepton and associated neutrino.

## 2. Studies in Single Top Quark Production

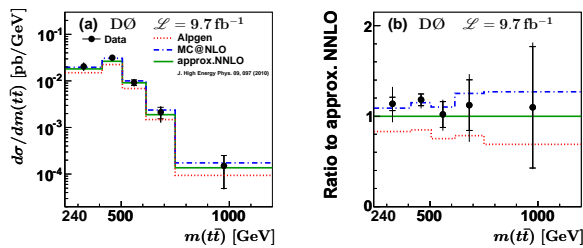
Top quarks can be produced in pairs via the strong interaction, or singly via the electroweak interaction. The latter occurs via s-channel, t-channel and  $Wt$ -channel production. The  $Wt$ -channel has a negligible cross section at the Tevatron, and only became relevant and observable at the LHC [3]. In 2009, CDF and D0 reported first observation of single top quark production [4, 5], where the s- and t-channel were measured together. For the observation, CDF and D0 were using up to  $3.2 \text{ fb}^{-1}$  and  $2.3 \text{ fb}^{-1}$  of data, respectively. The measurement of single top quark production is very challenging, as the main background from  $W$ +jets events looks very similar to the single top signature. Various multivariate techniques have been employed to distinguish the signal from the large background. The t-channel on its own has been first observed by D0 in 2011 [6] using  $5.4 \text{ fb}^{-1}$  of data.

Only recently, also the s-channel was observed by performing a combination of CDF and D0 measurements. The analyses employed for combination use up to the full Run II data sample. Semileptonic events are considered in the analyses by both collaborations, with the addition of an analysis by CDF, where events with a missing transverse energy plus jet signature are used, adding acceptance of events in which the lepton is not directly reconstructed. The events are required to contain at least two jets, of which one or two have to be identified as  $b$ -jet. A multivariate discriminant is build to separate s-channel signal from background. In this analysis, the  $t$ -channel single top production cross section was set to its SM value. The combined analysis results in a cross section of  $\sigma_s = 1.29^{+0.26}_{-0.24}$  pb, which deviates with more than 6.3 standard deviations (SD) from zero [7].

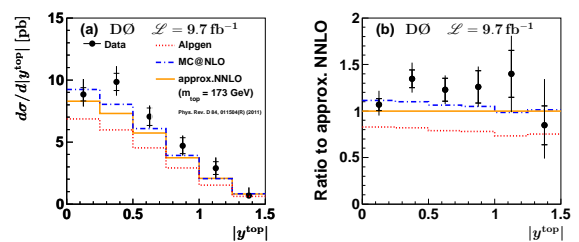
### 3. Studies in Top Quark Pair Production

The production of top quark pairs at the Tevatron is dominated by  $q\bar{q}$  annihilation with a fraction of approximately 85%, and consists of  $\approx 15\%$  gluon gluon fusion. At the LHC, these fractions are roughly inverse. Besides the different cross section of  $t\bar{t}$  production at the Tevatron relative to the LHC, these different fractions of production mechanisms are one of the main reasons why many analyses are complementary at the Tevatron relative to the LHC.

Recently, a new measurement of the  $t\bar{t}$  cross section inclusively and differentially as function of the invariant  $t\bar{t}$  mass,  $m_{t\bar{t}}$ , the rapidity of the top,  $|y^{top}|$ , and the transverse momentum of the top,  $p_T^{top}$ , has been performed by D0, using the full data sample of  $9.7 \text{ fb}^{-1}$  [8]. The measurement of the  $t\bar{t}$  production provides a direct test of Quantum Chromo Dynamics (QCD) by confronting the measurement with SM predictions. The analysis uses lepton+jets events, where the  $t\bar{t}$  event reconstruction is performed using a constrained kinematic fitter. The distributions are then corrected for detector and acceptance effects, using regularized unfolding, and are defined for parton-level top quarks including off-shell effects. Using events with at least four jets, the inclusive cross section has been measured as  $\sigma_{t\bar{t}} = 8.3 \pm 0.7(\text{stat}) \pm 0.6(\text{syst}) \pm 0.5(\text{lumi})$  pb, in good agreement with the SM prediction. Figure 1 and Fig. 2 show the unfolded  $t\bar{t}$  distributions as function of  $m_{t\bar{t}}$  and  $|y^{top}|$ , respectively, compared to approximate next-to-next-to-leading order (NNLO) calculations and different generator predictions. For these as well as the distribution as function of  $p_T^{top}$ , a good agreement between data and the NNLO calculations and generator predictions can be seen in general. In addition, a comparison to various axigluon models is performed. Using the differential distributions, these can be constrained.



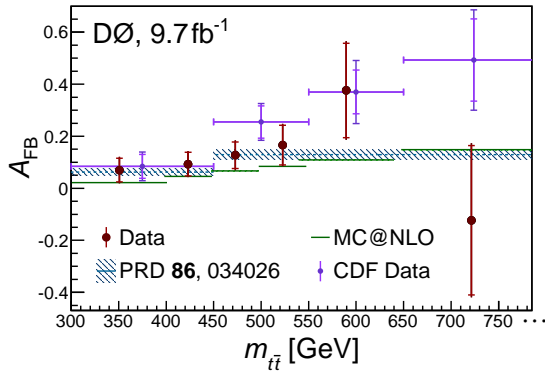
**Figure 1.** Differential  $t\bar{t}$  distribution as function of  $m_{t\bar{t}}$  [8].



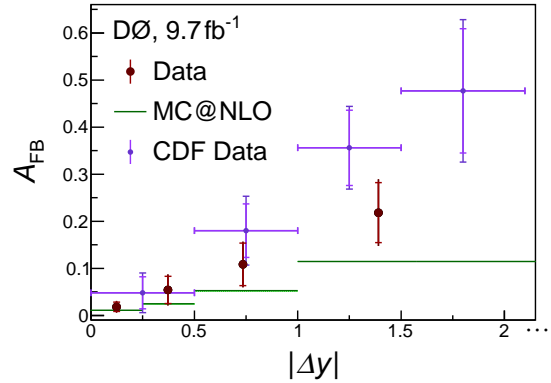
**Figure 2.** Differential  $t\bar{t}$  distribution as function of  $|\Delta y^{top}|$  [8].

An interesting feature of  $t\bar{t}$  production is the forward-backward asymmetry. At next-to-leading order (NLO), interference between different  $q\bar{q}$  diagrams causes a  $t\bar{t}$  asymmetry, where the top quarks are more likely to go into the direction of the incoming quark. Various asymmetries can be studied, in particular the forward-backward asymmetry  $A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$ , with  $N$  being the number of events with the difference in top and antitop rapidity  $\Delta y$  smaller

or larger zero, and the leptonic asymmetry  $A_{FB}^l = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$ , with  $q_l$  and  $y_l$  being the charge and rapidity of the lepton from  $W$  boson decay, respectively. The asymmetries have been measured using dileptonic and semileptonic events, and get unfolded to production level. The combined leptonic asymmetry in dileptonic and semileptonic events, using  $9.7 \text{ fb}^{-1}$  of D0 data, yields  $A_{FB}^l = 4.7 \pm 2.3(\text{stat}) \pm 1.5(\text{syst}) \%$  [9, 10], in good agreement with the SM prediction at NLO QCD, including electroweak (EW) corrections, of  $A_{FB}^l = 3.8 \pm 0.2 \%$  [11]. The asymmetry is also measured as function of lepton  $p_T$ , showing good agreement with the prediction from MC@NLO [13]. The measurement of the forward-backward asymmetry in the semileptonic channel explores events with three or at least four jets. The measured asymmetry is  $A_{FB}^{t\bar{t}} = 10.6 \pm 2.7(\text{stat}) \pm 1.3(\text{syst}) \%$  [12], in good agreement with the NLO+EW SM prediction of  $A_{FB}^{t\bar{t}} = 8.8 \pm 0.6 \%$  [11]. The measurement of  $A_{FB}^{t\bar{t}}$  as function of  $m_{t\bar{t}}$  and  $|\Delta y|$  is shown in Fig. 3 and Fig. 4, respectively. The differential  $A_{FB}^{t\bar{t}}$  distributions as function of the two observables show good agreement with the prediction from MC@NLO, but are also consistent with the recent measurement by CDF [14].



**Figure 3.**  $A_{FB}^{t\bar{t}}$  as function of  $m_{t\bar{t}}$  [12].



**Figure 4.**  $A_{FB}^{t\bar{t}}$  as function of  $|\Delta y^{top}|$  [12].

Another important analysis is the precise measurement of the top quark mass. The top quark mass is a free parameter in the SM. Together with the mass of the  $W$  boson, the top quark mass constrains the Higgs boson mass, and thus provides a self-consistency check. The D0 collaboration recently performed a new measurement of the top quark mass, using semileptonic events with at least one identified  $b$ -jet in the full Run II data sample of  $9.7 \text{ fb}^{-1}$ . For this, the matrix element technique is applied, which uses the full event kinematic and thus provides the most precise method. In this method, a probability is calculated for each event, where a phase space integration over leading order matrix elements, folded with parton distribution functions and transfer functions is performed. For the new analysis, the speed of the integration has been improved with respect to the previous implementation in D0. Furthermore, the handling of the systematic uncertainties has also been improved, allowing less conservative estimations of several sources of systematic uncertainties. To reduce the uncertainty from jet energy scale, jets from the hadronically decaying  $W$  boson are used as an in-situ constraint. The top quark mass is measured to be  $m_t = 174.98 \pm 0.58(\text{stat} + \text{JES}) \pm 0.49(\text{syst}) \text{ GeV}$  [15]. With a relative uncertainty of 0.43 %, this is the most precise single measurement of the top quark mass to date. The main systematic uncertainties originate from uncertainties on the residual jet energy scale, and hadronization and underlying event. Using this new measurement as well as updates on all-hadronic and dileptonic measurements by CDF, an updated Tevatron top quark mass combination has been performed. Using the BLUE method [16] for the combination of Run I and Run II results from CDF and D0 in various final states, the new Tevatron combination yields  $m_t = 174.34 \pm 0.37(\text{stat}) \pm 0.52(\text{syst}) \text{ GeV}$  [17].

In the SM, the top quark has an electric charge of  $+2/3$  of the electron charge. An exotic model could be possible though, where the top quark carries a charge of  $-4/3$  the electron charge. Using  $5.3 \text{ fb}^{-1}$  of data, D0 performed a new measurement of the top quark charge in semileptonic  $t\bar{t}$  events. In this analysis, at least four jets, of which at least two jets have to be identified as  $b$  jets, are required. To assign the final state objects to come from the top or antitop quark, a kinematic fitting algorithm is used. The top quark charge can then be determined by combining the charge of the lepton from the  $W$  boson decay with the charge of the  $b$  jet. The determination of the latter happens via a jet-charge algorithm, where a weighted sum of the charge of the tracks belonging to the  $b$  jet is calculated. The weight used in the sum is  $p_T^{0.5}$  of the respective tracks. The factor 0.5 in the exponent has been optimized using  $t\bar{t}$  events. The calibration of the jet charge algorithm is done using dijet events, where soft lepton and lifetime  $b$ -jet identification was applied. A SM and exotic top charge template is then constructed in  $t\bar{t}$  events, and the fraction  $f$  of the events with SM top charge is extracted using a binned maximum likelihood fit. The measured fraction  $f$  yields  $f = 0.88 \pm 0.13(\text{stat}) \pm 0.11(\text{syst})$  [18]. The dominant systematic uncertainty in this measurement is the statistics of the dijet sample. This value of  $f$  translates into the exclusion of the hypothesis that top quarks carry a charge of  $-4/3$  of the electron charge at more than five SD, confirming earlier results by CDF and ATLAS. An alternative interpretation of the measurement can be done, assuming that the  $t\bar{t}$  sample is a mixture of top quarks with charges  $+2/3$  and  $-4/3$ . This measurement results in an upper limit on the admixture of exotic top quarks of  $f < 0.46$  at 95% confidence level.

#### 4. Conclusion

Despite the Tevatron having been switched off about three years ago, the exploitation of the data are still ongoing. Many new measurements of top quark production and properties have been released recently by the D0 collaboration. Several of these are Tevatron legacies, for example the most precise single measurement of the top quark mass, the final word from D0 on the forward-backward asymmetry, and the measurement of a variety of differential  $t\bar{t}$  distributions.

#### Acknowledgments

I would like to thank my collaborators from the D0 collaboration for their help in preparing the presentation and this article. I also thank the staffs at Fermilab and collaborating institutions, and acknowledge the support from the Helmholtz association.

#### References

- [1] F. Abe *et al.* [CDF Collaboration], Phys. Rev. Lett. **74**, 2626 (1995).
- [2] S. Abachi *et al.* [D0 Collaboration], Phys. Rev. Lett. **74**, 2632 (1995).
- [3] CMS Collaboration, Phys. Rev. Lett. **112**, 231802 (2014).
- [4] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **103**, 092002 (2009).
- [5] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **103**, 092001 (2009).
- [6] V. M. Abazov *et al.* [D0 Collaboration], Phys. Lett. B **705**, 313 (2011).
- [7] T. Aaltonen *et al.* [CDF and D0 Collaborations], Phys. Rev. Lett. **112**, 231803 (2014).
- [8] V. M. Abazov *et al.* [D0 Collaboration], arXiv:1401.5785 [hep-ex] (submitted to PRD).
- [9] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **88**, 112002 (2013).
- [10] V. M. Abazov *et al.* [D0 Collaboration], arXiv:1403.1294 [hep-ex] (submitted to PRD).
- [11] W. Bernreuther and Z. -G. Si, Phys. Rev. D **86**, 034026 (2012).
- [12] V. M. Abazov *et al.* [D0 Collaboration], arXiv:1405.0421 [hep-ex] (submitted to PRD).
- [13] S. Frixione and B. R. Webber, J. High Energy Phys. **06**, 029 (2002).
- [14] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. D **87**, 092002 (2013).
- [15] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **113**, 032002 (2014).
- [16] L. Lyons, D. Gibaut, and P. Clifford, Nucl. Instrum. Meth. A **270**, 110 (1988); A. Valassi, Nucl. Instrum. Meth. A **500**, 391 (2003).
- [17] T. Aaltonen *et al.* [CDF and D0 Collaborations], arXiv:1407.2682 [hep-ex].
- [18] V. M. Abazov *et al.* [D0 Collaboration], arXiv:1407.4837 [hep-ex] (submitted to PRD RC).